

Black hole production and Large Extra Dimensions

Kingman Cheung*

National Center for Theoretical Sciences, National Tsing Hua University, Hsinchu, Taiwan, R.O.C.

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Black hole (BH) production at colliders is possible when the colliding energy is above the Planck scale, which can effectively be at TeV scale in models of large extra dimensions. In this work, we study the production of black holes at colliders and discuss the possible signatures. We point out the “ $ij \rightarrow \text{BH} + \text{others}$ ” subprocesses, in which the BH and other SM particles are produced with a large transverse momentum. When the BH decays, it gives a signature that consists of particles of high multiplicity in a boosted spherical shape on one side of the event and a few number of high p_T partons on the other side, which provide very useful tags for the event.

PACS numbers:

Introduction. Black hole (BH) has been an illusive object for decades, as we cannot directly measure any properties of it, not to mention the production of black holes in any terrestrial experiments. This is due to the fact that in order to produce black holes in collider experiments one needs a center-of-mass energy above the Planck scale ($M_P \sim 10^{19}$ GeV), which is obviously inaccessible at the moment.

Since the second revolution of string theories, a crop of models with extra dimensions have been proposed to solve various theoretical problems. In an attractive model of large extra dimensions or TeV quantum gravity [1], the effective Planck scale can be as low as a few TeV. This is made possible by localizing the standard model (SM) particles on a brane (using the idea of D-branes in Type I or II string theory), while gravity is free to propagate in all dimensions.

The fact that the effective Planck scale is as low as TeV opens up an interesting possibility of producing a large number of black holes [2, 3, 4] at collider experiments (e.g. LHC). Reference [4] also showed that a BH localized on a brane will radiate mainly in the brane, instead of radiating into the Kaluza-Klein states of gravitons of the bulk. In this case, the BH so produced will decay mainly into the SM particles, which can then be detected in the detector. This opportunity has enabled investigation of the properties of BH at terrestrial collider experiments.

A black hole is characterized by its Schwarzschild radius R_{BH} , which depends on the mass M_{BH} of the BH. A simplified picture for BH production is as follows. When the colliding partons have a center-of-mass (c.o.m.) energy above some thresholds of order of the Planck mass and the *impact parameter* less than the Schwarzschild radius R_{BH} , a BH is formed and almost stationary in the c.o.m. frame. The BH so produced will decay thermally (regardless of the incoming particles) and thus isotropically in that frame.

This possibility has been investigated in a few recent work at the LHC [5, 6, 7, 8], and at cosmic ray experiments [9, 10, 11]. In Refs. [5, 6, 7] black hole production in hadronic collisions is calculated in $2 \rightarrow 1$ subprocesses:

$ij \rightarrow \text{BH}$, where i, j are incoming partons. The black hole so produced is either at rest or traveling along the beam pipe such that its decay products (of high multiplicity) have a zero net transverse momentum (p_T). Dimopoulos and Landsberg [6] demonstrated that a BH so produced will decay with a high multiplicity [6]. Banks and Fischler [3] pointed out that one of the most striking signature of BH production would be a complete cutoff of process with p_T larger than R_{BH}^{-1} because the incoming partons can never get close enough to perform an extremely hard QCD scattering.

In this Letter, we point out the “ $ij \rightarrow \text{BH} + \text{others}$ ” subprocesses, such that the BH is produced with a large p_T before it decays. In such subprocesses, the “others” are just the ordinary SM particles and usually of much lower multiplicity than the decay products of the BH. Therefore, the signature would be very striking: on one side of the event there are particles of high multiplicity (from the decay of the BH), the total p_T of which is balanced by a much fewer number of particles on the other side. Such a signature is very clean and should have very few backgrounds.

The “ $ij \rightarrow \text{BH} + \text{others}$ ” subprocesses can be easily formed when the c.o.m. energy of the colliding particles are larger than the BH mass, the excess energy will be radiated as other SM particles. Thus, a picture of $ij \rightarrow \text{BH} + \text{others}$ is justified. Besides, such processes are of immense interests because they involve qualitatively new phenomena, e.g., violation of global quantum (lepton, baryon) numbers. The resulting cross section is large enough for detection. Even at $p_T > 500$ GeV the production cross section is as large as 24 fb for $n = 4$, $M_D = 1.5$ TeV, and $y \equiv (M_{\text{BH}})_{\text{min}}/M_D = 5$ (a BH with a mass ≥ 7.5 TeV), which gives 2400 clean events for an integrated luminosity of 100 fb $^{-1}$ at the LHC, as will be shown later. The event rate is still large enough for detection. Here we have imposed a very restricted requirement on the BH entropy ($S_{\text{BH}} \gtrsim 25$) to ensure the validity of the classical BH description. Otherwise, if we relaxed this entropy constraint the production cross sections would be increased tremendously, but the cross

sections have to be interpreted with care because of the presence of large string effects in this regime.

Production. The Schwarzschild radius R_{BH} of a BH of mass M_{BH} in $4+n$ dimensions is given by [12]

$$R_{\text{BH}} = \frac{1}{M_D} \left(\frac{M_{\text{BH}}}{M_D} \right)^{\frac{1}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{n+3}{2})}{n+2} \right)^{\frac{1}{n+1}}, \quad (1)$$

where M_D is the effective Planck scale in the model of large extra dimensions defined by

$$M_D^{n+2} = \frac{(2\pi)^n}{8\pi G_{4+n}}, \quad (2)$$

where G_{4+n} is the gravitational constant in $D = 4+n$ dimensions (used in the Einstein equation: $\mathcal{R}_{AB} - \frac{1}{2}g_{AB}\mathcal{R} = -8\pi G_{4+n}T_{AB}$.) The radius is much smaller than the size of the extra dimensions. BH production is expected when the colliding partons with a center-of-mass energy $\sqrt{\hat{s}} \gtrsim M_{\text{BH}}$ pass within a distance less than R_{BH} . A black hole of mass M_{BH} is formed and the rest of energy, if there is, is radiated as ordinary SM particles. This semi-classical argument calls for a geometric approximation for the cross section for producing a BH of mass M_{BH} as

$$\sigma(M_{\text{BH}}^2) \approx \pi R_{\text{BH}}^2. \quad (3)$$

In the $2 \rightarrow 1$ subprocess, the c.o.m. energy of the colliding partons is just the same as the mass of the BH, i.e., $\sqrt{\hat{s}} = M_{\text{BH}}$, which implies a subprocess cross section

$$\hat{\sigma}(\hat{s}) = \int d\left(\frac{M_{\text{BH}}^2}{\hat{s}}\right) \pi R_{\text{BH}}^2 \delta(1 - M_{\text{BH}}^2/\hat{s}) = \pi R_{\text{BH}}^2. \quad (4)$$

On the other hand, for the $2 \rightarrow n$ ($n \geq 2$) subprocesses the subprocess cross section is

$$\hat{\sigma}(\hat{s}) = \int_{(M_{\text{BH}}^2)_{\min}/\hat{s}}^1 d\left(\frac{M_{\text{BH}}^2}{\hat{s}}\right) \pi R_{\text{BH}}^2. \quad (5)$$

Another important quantity that characterizes a BH is its entropy given by

$$S_{\text{BH}} = \frac{4\pi}{n+2} \left(\frac{M_{\text{BH}}}{M_D} \right)^{\frac{n+2}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{n+3}{2})}{n+2} \right)^{\frac{1}{n+1}}. \quad (6)$$

To ensure the validity of the above classical description of BH [13], the entropy must be sufficiently large, of order 25 or so. We verified that when $M_{\text{BH}}/M_D \gtrsim 5$, the entropy $S_{\text{BH}} \gtrsim 25$, below that string effects are important. Therefore, to avoid getting into the nonperturbative regime of the BH and to ensure the validity of the semi-classical formula, we restrict the mass of the BH to be $M_{\text{BH}} > yM_D$, where $y \equiv (M_{\text{BH}})_{\min}/M_D$ is of order 5.

Voloshin [8] pointed out that the semi-classical argument for the BH production cross section is not given

by the geometrical cross section area, but, instead, suppressed by an exponential factor:

$$\exp\left(-\frac{S_{\text{BH}}}{n+1}\right). \quad (7)$$

The suppression factor makes the production of BH concentrate on M_{BH} close to M_D . Thus, if the available energy in the collision is larger than the M_D the rest of energy is more likely to radiate as the SM particles. There are, however, counter arguments [13, 14] that the simple geometric formula should be valid.¹

In this work, we first consider both forms of cross sections: (i) the naive πR_{BH}^2 and (ii) the πR_{BH}^2 multiplied with the exponential factor of Eq. (7). But we shall see immediately that the suppression factor renders the cross section to be too small for detection. In Fig. 1, we show the differential cross section $d\sigma/dM_{\text{BH}}$ for the process $pp \rightarrow \text{BH} + 1$ parton at the LHC for $n = 4$, $y \equiv (M_{\text{BH}})_{\min}/M_D = 5$ and $M_D = 1.5$ TeV, which is consistent with the existing limit on M_D [16]. We can see that when the exponential suppression factor is used the spectrum of M_{BH} will shift closer to M_D . The average value $\langle M_{\text{BH}} \rangle$ for the geometric approximation is about 8.0 TeV while using the exponential suppression factor the $\langle M_{\text{BH}} \rangle \simeq 7.8$ TeV. However, the cross section is suppressed more than two orders of magnitude relative to the naive geometric cross section. From here on we shall not concern this suppression factor anymore. We also show the graphs for $y = 2.5$, a less stringent requirement on the BH entropy. Obviously, the production cross section is much larger. However, careful interpretation is needed because in this BH mass region it might involve nonperturbative string corrections.

The main difference between the $2 \rightarrow 1$ and $2 \rightarrow n$ ($n \geq 2$) subprocesses is that in $2 \rightarrow n$ the BH will have a transverse momentum. We approximate the $2 \rightarrow n$ subprocess by a $2 \rightarrow 2$ subprocess and assume the BH is produced in association with a massless parton. Since the mass of the BH is larger than the effective Planck mass, the c.o.m. energy $\sqrt{\hat{s}} \geq M_{\text{BH}}$ is of order of a few TeV and would give a large transverse momentum to the BH. We show in Fig. 2 the transverse momentum spectrum for the production $pp \rightarrow \text{BH} + 1$ parton. The average value of p_T is about 330 GeV for $n = 4$, $M_D = 1.5$ TeV and $y = 5$.

Decay. The main phase of the decay of BH is via the Hawking evaporation. The evaporation rate is governed by its Hawking temperature, which is given by [12]

$$T_{\text{BH}} = \frac{n+1}{4\pi R_{\text{BH}}} \quad (8)$$

¹ There is also a counter-counter argument from Voloshin [15]. Nevertheless, before the issue is resolved we present the results with and without the suppression factor.

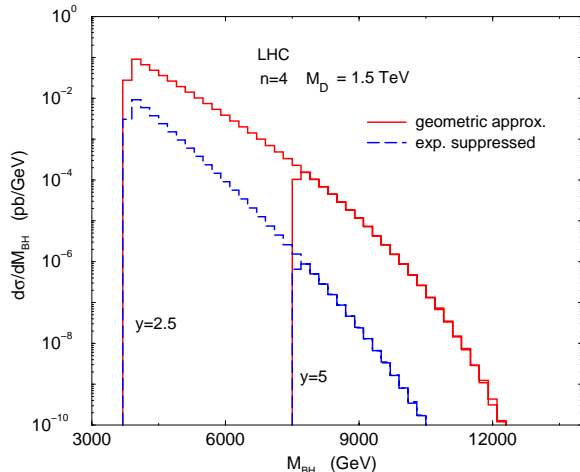


FIG. 1: The differential cross section $d\sigma/dM_{\text{BH}}$ for $pp \rightarrow \text{BH} + 1 \text{ parton}$ versus the mass M_{BH} at the LHC for $n = 4$, $M_D = 1.5 \text{ TeV}$ and $y \equiv (M_{\text{BH}})_{\text{min}}/M_D = 2.5, 5$. “Geometric approx.” means that we used Eq. (3) to calculate the cross section while “exp. suppressed” means that we also included the suppression factor in Eq. (7).

which scales inversely with some powers of M_{BH} . The heavier the BH the lower the temperature is. Thus, the evaporation rate is slower. The lifetime of the BH scales inversely with the Hawking temperature as given by

$$\tau \sim \frac{1}{M_D} \left(\frac{M_{\text{BH}}}{M_D} \right)^{\frac{n+3}{n+1}}. \quad (9)$$

From the above equation, it is obvious to see that the lifetime of a BH becomes much longer in models of large extra dimensions than in the usual 4D theory. However, the lifetime is still so short that it will decay once being produced and no displaced vertex can be seen in the de-

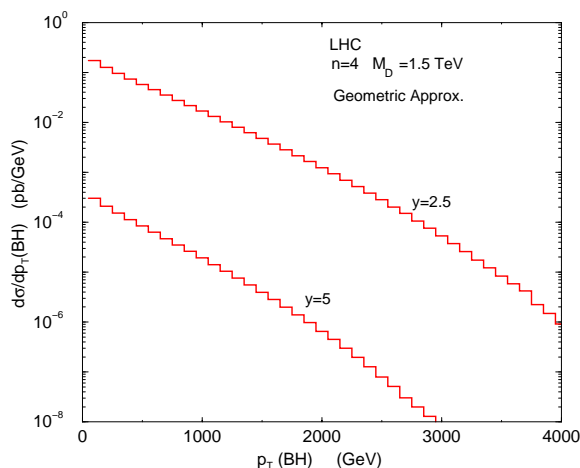


FIG. 2: The transverse momentum spectrum for the BH production in association with a massless parton at the LHC for $n = 4$, $M_D = 1.5 \text{ TeV}$ and $y \equiv (M_{\text{BH}})_{\text{min}}/M_D = 2.5, 5$.

tector. For another view point on the BH decay please see Ref. [17].

Another important property of the BH decay is the large number of particles, in accord with the large entropy in Eq. (6), in the process of evaporation. Dimopoulos and Landsberg [6] showed that the average multiplicity $\langle N \rangle$ in the decay of a BH is order of $10 - 30$ for M_{BH} being a few times of M_D for $n = 2 - 6$. Since we are considering the BH that has an entropy of order 25 or more, it guarantees a high multiplicity BH decay. The BH decays more or less isotropically and each decay particle has an average energy of a few hundred GeV. Therefore, if the BH is stationary, the event is very much like a spherical event with many particles of hundreds of GeV pointing back to the interaction point. Moreover, the ratio of hadronic to leptonic activities in the BH decay is about $5 : 1$ [5]. On the other hand, if the BH is produced in association with other SM particles (as in $2 \rightarrow n$ subprocesses), the BH decay will be a boosted spherical event on one side, the transverse momentum of which is balanced by a few number of particles on the other side. A cartoon for such a typical event in the (y, z) plane is shown in Fig. 3. This is a high p_T event. On one side of the event is the decay products of high multiplicity of the BH in a boosted spherical shape. The original momentum of the BH in the (y, z) plane is also shown, which is balanced by the momentum of the energetic parton, which is on the other side of the event. Such spectacular events should have negligible background.

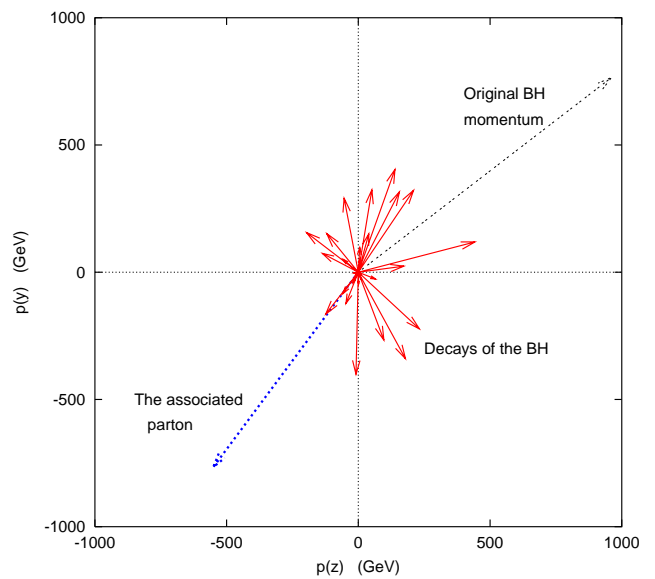


FIG. 3: A cartoon showing a typical event of black hole production with a large transverse momentum.

In addition, since at the LHC multi-parton collisions and overlapping events may be likely to happen, a careful discrimination is therefore necessary, especially, in the case that the BH is produced at rest or moving along the

beam-pipe (i.e. in $2 \rightarrow 1$ subprocess). In our study, the $2 \rightarrow 2$ subprocess affords an easier signature experimentally. The high p_T parton emerging as a jet, a lepton, jets, or leptons provides an easy tag.

Another concern of BH production is the event rate because the higher the p_T the smaller the cross section is. The production cross section for $p_T > 500$ GeV is as large as 24 fb for $n = 4, M_D = 1.5$ TeV and $y \equiv (M_{\text{BH}})_{\text{min}}/M_D = 5$, which corresponds to 2400 events for an integrated luminosity of 100 fb^{-1} . Such a large number of clean events should be observable at the LHC. The production cross sections for other values of n, M_D and y are listed in Table I. The cross sections listed for $y \equiv (M_{\text{BH}})_{\text{min}}/M_D \lesssim 4$ should be interpreted with care, because the smaller the ratio $(M_{\text{BH}})_{\text{min}}/M_D$ the stronger the string effect is and the classical description for BH may not be valid. Nevertheless, the numbers listed here can be used for comparison with other published results.

In this paper, we have emphasized the importance and the advantages of using the $2 \rightarrow 2$ subprocess for BH production, which allows a substantial transverse momentum kick to the BH, and at the same time produce an energetic high p_T parton, which provides a critical tag to the event. The observation here serves as an interesting extension to the previous work, in which the consideration is only given to BH production with the BH at rest.

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* Email: cheung@phys.cts.nthu.edu.tw

TABLE I: Cross sections in pb for BH production in “ $2 \rightarrow 2$ ” subprocess for various values of n , M_D and $y \equiv (M_{\text{BH}})_{\text{min}}/M_D$ at the LHC. The transverse momentum cut is $p_T > 500$ GeV. The cross sections are calculated using the geometric approximation of Eq. (3). The cross sections given in the parenthesis are for the “ $2 \rightarrow 1$ ” subprocess, i.e., with zero p_T and the BH at rest. For $M_D = 3$ TeV and $y = 5$ the minimum mass for the BH is already larger than the energy of the LHC.

Cross section in pb				
	$n = 3$	$n = 4$	$n = 5$	$n = 6$
<u>$M_D = 1.5$ TeV</u>				
$y = 1$	351 (5300)	571 (8650)	820 (12400)	1090 (16600)
$y = 2$	40.1 (540)	62.8 (831)	87.1 (1150)	113 (1490)
$y = 3$	4.2 (70.4)	6.3 (105)	8.6 (142)	10.9 (180)
$y = 4$	0.34 (8.1)	0.49 (11.8)	0.65 (15.7)	0.82 (19.8)
$y = 5$	0.017 (0.68)	0.024 (0.97)	0.032 (1.3)	0.039 (1.6)
<u>$M_D = 2$ TeV</u>				
$y = 1$	83.9 (1120)	137 (1840)	198 (2650)	264 (3540)
$y = 2$	4.5 (67.8)	6.9 (105)	9.7 (145)	12.5 (188)
$y = 3$	0.16 (4.0)	0.25 (5.9)	0.33 (8.0)	0.43 (10.3)
$y = 4$	0.0026 (0.13)	0.0038 (0.19)	0.0051 (0.25)	0.0064 (0.32)
$y = 5$	7×10^{-6} (0.0012)	1.1×10^{-5} (0.0017)	1.4×10^{-5} (0.0022)	1.7×10^{-5} (0.0028)
<u>$M_D = 3$ TeV</u>				
$y = 1$	7.2 (95.5)	11.9 (157)	17.3 (228)	23.1 (305)
$y = 2$	0.06 (1.4)	0.09 (2.2)	0.13 (3.1)	0.17 (4.1)
$y = 3$	0.69×10^{-4} (0.0056)	1.0×10^{-4} (0.0084)	1.4×10^{-4} (0.011)	1.8×10^{-4} (0.015)
$y = 4$	7×10^{-11} (1.8×10^{-7})	1.1×10^{-10} (2.6×10^{-7})	1.4×10^{-10} (3.5×10^{-7})	1.8×10^{-10} (4.5×10^{-7})
$y = 5$	-	-	-	-